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Studies on water vapour over a coastal region

P K Karmakar, P K Tarafder*, S Chattopadhyay and A K Sen
Institute of Radiophysics and Electronics, University of Calcutta,
92, A P C Road, Calcutta-700 009, India

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Abstract : The vertical distribution of water vapour over a coastal location has been studied. Tropospheric water vapour distribution normally shows an exponential distribution, with a water vapour scale height at 2 km The most significant water vapour height that influences the integrated water vapour content is addressed The significant height is located between 1.5–2.5 km Water vapour effect in millimeterwave propagation and dispersive delay are also addressed Results show that the significant height lies between 1 5–2.5 km. This has a vital role in influencing the integrated water vapour content

Keywords : Water vapour, vertical distribution, coastal region

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1. Introduction

Water vapour, although a minor atmospheric constituent (0–4% by volume), plays an important role in thermodynamic processes because it can change phase. Further, it is one of the important constituents from the meteorological view point for maintaining the hydrological cycle by transpiration and evaporation. The hydrological cycle involves the conversion of water vapour to precipitation in the form of rain or snow. Thus a knowledge of this element is necessary. Near the surface we have a boundary layer with diurnal variation, while in the upper troposphere we have only a small amount of water vapour. An optimum height is thus expected where the correlation would be significant between the density variation of water vapour at individual heights and the integrated density (0–10 km) of water vapour. We wish to explore the relative contribution of water vapour at different altitudes towards the integrated water vapour content. This vapour content is measured in a cylinder of base area 1 m^2 and height, 10 km.

Remote sensing of water vapour in the microwave and millimeter wave band has led us to exploit the resonant lines as well as windows. An important reason for using radio

*Present Address . TIL Ltd., Kamarhatty Works, 517, B T Road, Calcutta-700 058, India

windows is their capability of penetrating clouds and their independence on the sun as a source of illumination. On the other hand, the millimetric wave band provides an additional set of factors, not generally considered at lower frequency bands. This includes the interaction between electromagnetic radiation and the polar molecules of the earth's atmosphere, *i.e.* water vapour and oxygen. This interaction manifests itself in terms of the complex refractive index of the propagation medium. The imaginary part of this refractive index provides attenuation and the real part provides the dispersion or propagation delay. Attenuation can then be inverted to find the water vapour concentration. For this inversion one has to take care of an intrinsic property of the water vapour attenuation profile. As attenuation due to water vapour is approximately linear with absolute humidity, we have

$$K(\rho) = A \times \rho$$

where K is attenuation coefficient (dB/Km), A is a constant and ρ is the absolute humidity (g/m^3). The profile of humidity can be approximated by

$$\rho(h) = \rho_0 \exp\left(-h/h_0\right),$$

where ρ_0 is the surface humidity, h is the altitude and h_0 is the scale height.

Theoretical estimates of the attenuation rate indicate that under clear skies, the millimeter wave attenuation due to atmospheric gases exhibit minima around 35, 94, 140 and 220 GHz. Theoretical studies have also been extended to find the effect of water vapour at these window frequencies.

2. Analyses and results

A. Relative contribution of water vapour at different altitudes :

We explore the relative contribution of water vapour at different altitudes towards an integrated water vapour content. To accomplish this, we have analysed the radiosonde data for the Monsoon experiment period (MONEX, 1979), over Digha (21°40′ N; 87°40′ E), located on the northern coast of Bay-of-Bengal, collected by the India Meteorological Department (IMD), Government of India. The radiosonde data during the MONEX period (July–August, 1979) were taken four times a day at 00.00, 06.00, 12.00 and 18.00 GMT corresponding to 05.30, 11.30, 17.30 and 23.30 IST (Indian Standard Time) respectively. The data consist of pressure, P (hPa), temperature T(°C), dew point temperature T_D(°C) at different altitudes over Digha, a coastal region. The saturation vapour pressure (hPa) was calculated from the radiosonde data by using the relation [1],

$$e = 6.105 \exp\left[25.22\left(1 - 273/T_D\right) - 5.31 \ln\left(T_D/273\right)\right]. \quad (1)$$

The water vapour density was then deduced from vapour pressure by the relationship,

$$\rho\left(g/m^3\right) = \left[e \times 18 \times 10^2\right]/\left[8.31 \times T\right] = \frac{e}{T} \times 216.60. \quad (2)$$

A statistical formula was then used to find out the correlation of temporal variation of water vapour density, at different heights in the range 0–10 km, averaged over 6, 12 and 24 hours, with the variation of the integrated water vapour content, $\omega(\mathrm{gm/m^2})$.

We note that 6 hourly averaging means the average of the data taken at 05.30 and 11.30 IST. Subsequently, 12 hourly averages are represented by the average of the data taken at 05.30, 11.30 and 17.30 IST. For a 24 hourly average, the average of all the observations taken on a day, were used. The correlation coefficient

$$r = \mathrm{COV}(\omega,\rho)/\sigma_\omega\sigma_\rho$$

Here σ_ω and σ_ρ are the standard deviations of ω and ρ respectively, and COV(ω, ρ) denotes the covariance of ω and ρ. Now, substituting the explicit expression for COV(ω, ρ), σ_ω , σ_ρ and multiplying the numerator and denominator by the number of observations, we write

$$r = \sum(\omega - \bar{\omega})(\rho - \bar{\rho}) \Big/ \sqrt{\left[\left(\sum\omega^2 - \bar{\omega}^2\right)\left(\sum\rho^2 - \bar{\rho}^2\right)\right]}$$

$$= \left(\sum\omega \times \rho - n\bar{\omega}\bar{\rho}\right) \Big/ \sqrt{\left[\left(\sum\omega^2 - n\bar{\omega}^2\right)\left(\sum\rho^2 - \bar{\rho}^2\right)\right]} \qquad (3)$$

where n represents the number of observations.

It is to be noted here that the correlation coefficient is unaffected by the choice of the origin and scale of both the variables. This is done by reducing the values of ω and ρ on

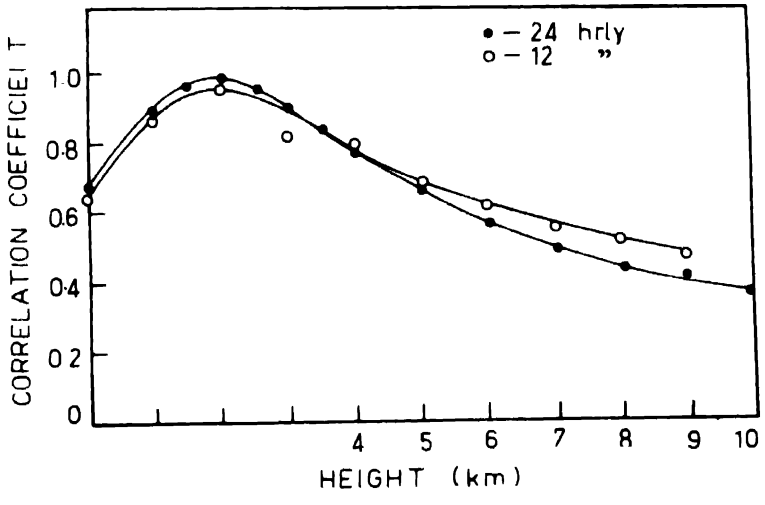

Figure 1. Correlation of temporal variation of water vapour density at different heights and the integrated water vapour density in the range 0–10 km. Data utilised four times a day for two months period (July–August)

subtracting the conveniently chosen constant numbers c and c'. Thus, we get reduced values of $\omega = (\omega - c)$ and $\rho = (\rho - c')$ from which the variables were calculated. Finally, the correlation coefficient was calculated by using eq. (3). In doing so, the absolute humidity,

ρ_1 at height h_1 (km), and the integrated water vapour ω at a time are considered to be a bivariate (ω, ρ_1). This process has been repeated by finding other set of bivariates (ω, ρ_2) and (ω, ρ_3) and so on. The results obtained are shown in Figure 1. We find that the correlation is maximum around 2 km for the averaging time of 12 and 24 hours [2]. For a 6 hourly averaging time, there does not exist any appreciable correlation. This height represents the diurnal variation pattern of integrated water vapour content.

B. Effect of water vapour on propagation delay :

Propagation delay is a parameter which is being applied as a correction factor for atmospheric attenuation for microwave scatterometers. It is also useful for infra-red radiometers. The delay introduced by tropospheric water vapour for radio signals in the VHF, UHF, microwave and millimeter wave bands may be comparable to, or even greater than the ionospheric delay.

The tropospheric propagation delay and attenuation are related to the complex refractive index. The imaginary part of this corresponds to the absorption and the real part represents the delay equivalent to an apparent path increase. The real part can be written as

$$\text{Re}\ (N) = 77.67\ P/T + 64.8\ e/T + 3.776 \times 10^5\ e/T^2, \tag{4}$$

where P is the dry air pressure (hPa), T is the atmospheric temperature (K) and e is the partial pressure of water vapour [3]. The first part of eq. (4) represents the contribution towards refractive index owing to the dry part of the atmosphere.

Detailed discussions on refractivity have been made by Bean and Dutton [4]. It is explained that the refractivity of molecules with permanent dipole moment varies with pressure and temperature. Water vapour and other minor trace constituents have permanent dipole moments in the atmosphere. The refractivity has a seasonal dependence which is similar to the seasonal dependence of water vapour. By using the same data set, as used in the previous section, tropospheric group delay has been estimated from the available data of refractivity [eq. (4)] with radiosonde data. It is given by

$$\tau = \frac{10^{-6}}{C} \int_0^h \text{Re}\ (N) dh, \tag{5}$$

where τ = tropospheric group delay and N is the refractivity, C is the velocity of light and h is the height in the troposphere (0–10 km).

Now, for exploring the contribution of water vapour to refractivity and subsequently to the delay, we express eq. (4) by

$$\text{Re}\ (N) = 64.8\ e/T + 3.776 \times 10^5\ e/T^2. \tag{6}$$

We have neglected the dry contribution to the refractivity to find the role of water vapour only on propagation delay.

Thus, to obtain an estimate of group delay, the refractivity profiles were integrated for the desired height. These profiles were drawn for 00, 06, 12, 18 GMT over the same location.

A sample plot of refractivity *versus* altitude is given in Figure 2. The group delays were then calculated by eq. (5).

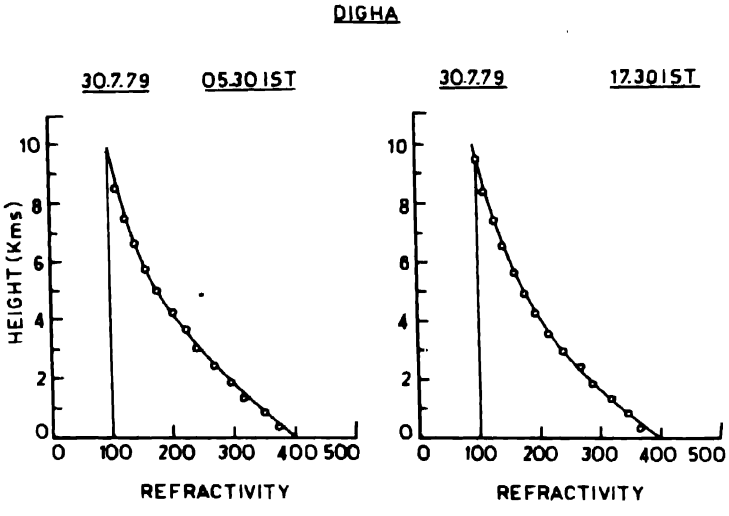

Figure 2. A plot of refractivity *versus* altitude over Digha

The same statistical formula has been employed to find the correlation between the refractivity at different heights and the group delay due to water vapour. This is pictorially presented in Figure 3. We see from Figure 3 that at 11.30 IST the correlation is good and is

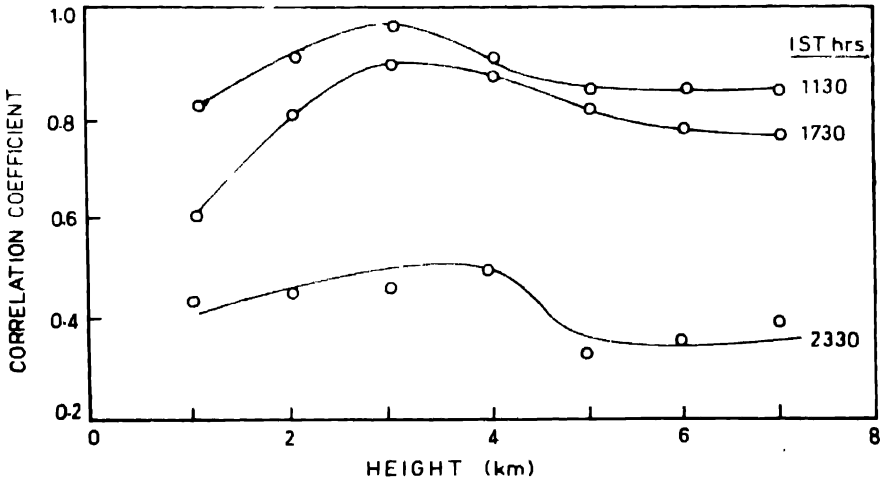

Figure 3. Correlation between refractivity due to wet part at different heights and the grouped delay for the range (0–10 km).

found to be 0.99 around 2–2.5 km. It reduces to 0.82 at about 5 km. At 17.30 IST, the correlation is 0.89 at 2–2.5 km, and drops to 0.75 around 5 km. On the other hand, at 23.30 and 05.30 IST there exist poor correlations. From this analysis, we notice that during late

night and morning, the correlation is found to be very poor. This suggests that during day-time, vertical transport of water vapour takes place, which makes the atmosphere turbulent. Here, we have restricted ourselves to present the data within 7–8 km as depicted in Figure 3, because we observed through computational analysis that the trend of correlation falls very rapidly as we go on to higher altitudes. This helps us to infer that the water vapour density around 2 km is the most significant height. Of course, this is valid for the time scale of 12–24 hours as discussed earlier.

C Absorption at millimeter wave bands due to water vapour :

The absorption exhibited by gaseous molecules possessing a permanent electric dipole moment is due to the coupling of the electric dipole with the electric component of the incident electromagnetic wave. This causes a change in the rotational quantum level, thereby producing the absorption spectra. However, the absorption spectra of water vapour (asymmetric rotor) molecules is complicated not only by the irregular distribution of energy levels, but also by the complexity of selection rules and the transition probabilities between the levels. The centrifugal distortion is important in the microwave spectrum of asymmetric rotors. In the case of symmetric tops, it produces very small shifts of the order of 1 Mc/S or less but for asymmetric tops, centrifugal distortions change the rotational frequencies by many hundreds of Mc/S [5].

However, the influence of polar molecules on the microwave and millimeterwaves is discussed thoroughly by Liebe [6] and also developed a Millimeterwave Propagation Model (MPM) which is based on the atmospheric complex refractivity. It predicts propagation loss and delay for the neutral atmosphere. In doing so, moist air refractivity is obtained by considering all resonant, far-wing and non-resonant radiowave interactions with gaseous molecules. However, we have selected some important resonant frequencies and window frequencies as shown in Figure 4.

Figure 4 shows the variation of attenuation coefficients (dB/km) with absolute humidity (g/m^3) for the frequencies of interest.

As, we wish to find out the effect of water vapour on radiowaves in the millimeterwave band, we have focussed only on the water vapour attenuation. Although, oxygen has contributions on millimeter waves, its effect is considered to be invariant because of the non-variant nature of oxygen concentration.

To illustrate the effect of water vapour on millimeter wave band, we have used the meteorological data for this purpose. Now, using the MPM model (6), the attenuation coefficients were found out for 22.235, 35, 50, 60 and 94 GHz. This gives us the height distribution of attenuation coefficients due to water vapour for the above frequencies.

With these results in hand, we were prompted to find out attenuation (dB/km) due to water vapour only, integrated upto 10 km. For this purpose, attenuation coefficients (dB/km) at different heights of the atmosphere were found out. This provides the attenuation distribution with height, four times a day over a two month period of July and August. These two months period are the maximum water vapour bearing months over the

east coast. Now, with all these distribution of attenuation data, a statistical method has been adopted to find out the best fit between attenuation coefficient and the corresponding height. These best fit relations were eventually found to be of exponential nature.

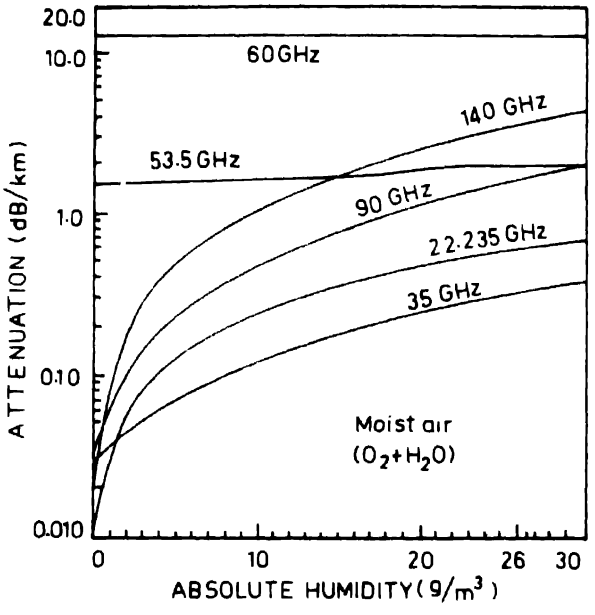

Figure 4. Attenuation due to moist air at Millimeter wave-lengths

Now, with these exponential equations, normal integration procedure was adopted within the specified height limit *i.e.* from ground to 1 km, from ground to 2 km and so on. This virtually gives the water vapour attenuation (dB) only for the specified heights,

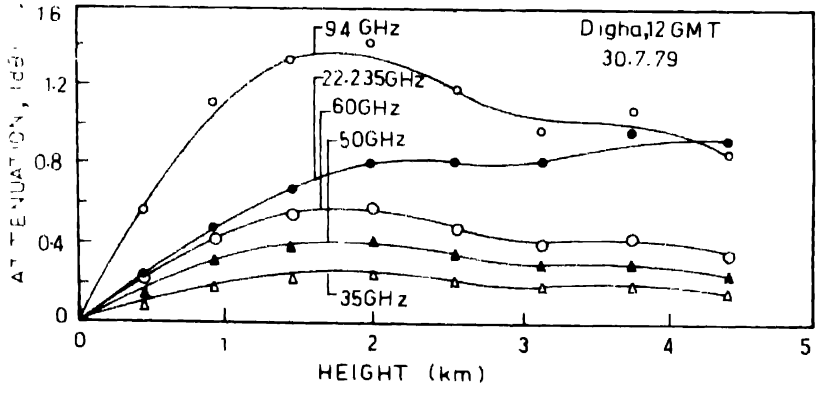

Figure 5. Attenuation in dB at 22, 35, 50, 60, 94 GHz at different heights

provided we assume water vapour is homogeneously distributed in the atmosphere. These findings of attenuation (dB) at 22.235, 35, 50, 60, 94 GHz have been plotted against the desired height (Figure 5). The most interesting nature of this figure is the presence of a

broad maxima at or around 2 km for all frequencies. This maxima would not have been present if the atmospheric water vapour had been well mixed. So we conclude that the water vapour is not well mixed. On the contrary, it shows a significant height which seems to be the significant height of water vapour.

3. Discussion and conclusion

In the first part of section I, we found that there exists a significant height of water vapour around 2 km.

In the second part of section II, we found that the variation of the refractivity profile at 2 km correlates most with the propagation delay.

In the third part of section II, we have found that the water vapour content at or around 2 km would influence the power loss variational pattern. This is based on a single case only *i.e.* for the day 30 July, 1979 and at 12.00 GMT. But we presume that this type of study for the other days or for the whole set of data *i.e.* for four times a day (during July–August), would be the representative for single case only. We conclude that the most significant height for water vapour is around 1.5 to 2.5 km, around which the variational pattern of attenuation would be the representative of water vapour attenuation (dB) variation for the entire height range *i.e.* within the height range, 0–10 km.

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